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J. Järvik

Novel Power Factor Correction Method and topology for AC/DC converters

I. INTRODUCTION

The input impedance of typical uncorrected AC/DC converters varies in each mains half-cycle. Thus, shape of mains current is badly distorted and different from the shape of mains voltage. The result is a decreased power factor. To solve this problem, there are passive, active and so-called "indirect" methods for power factor correction.

The first one uses a network frequency LC circuits operating as a higher frequency harmonic filter [1]. There is also a PSA converter (converter with Parallel and Series resonance Alternation) where resonant components L and C form a parallel or series resonant circuits of network frequency depending on load parameters [2]. The PSA converter, as studied before in [2],[6] has inherent short-circuit proof topology and fast parametrical (without control) output voltage/current adjusting to load variations. Both topologies reduce higher harmonics in mains current. Their advantage is simplicity, but large weight, size and cost of reactive components are drawbacks.

Nowadays, there are widely presented active methods for power factor correction [3]. Mostly, there is a boost and flyback PFC converters for this purpose. The advantage of the method is a reduced weight and size of coils and capacitors because of higher switching frequency. The disadvantage, it is an additional converter, which usually cannot be simultaneously applied for wide regulation of the rectified voltage. Another disadvantage is a relatively complicated control circuit.

And there are also known indirect power factor correction methods, which are the most close to the presented research. According to this method, waveform of mains current is not shaped directly, but by keeping converter impedance constant with the help of controlled modulators. [4]. Thus, mains current waveform automatically becomes similar to mains voltage waveform and no distortion appears in current waveform. This is an advantage of the method. The disadvantage of this method implementation is a large number of switches of the modulator and complicated control. In principle, input impedance could be kept constant by using matching transformer having fast-changing turns ratio [5]. The realization of such transformer using passive components is not known and drawback of active components realization is complexity.

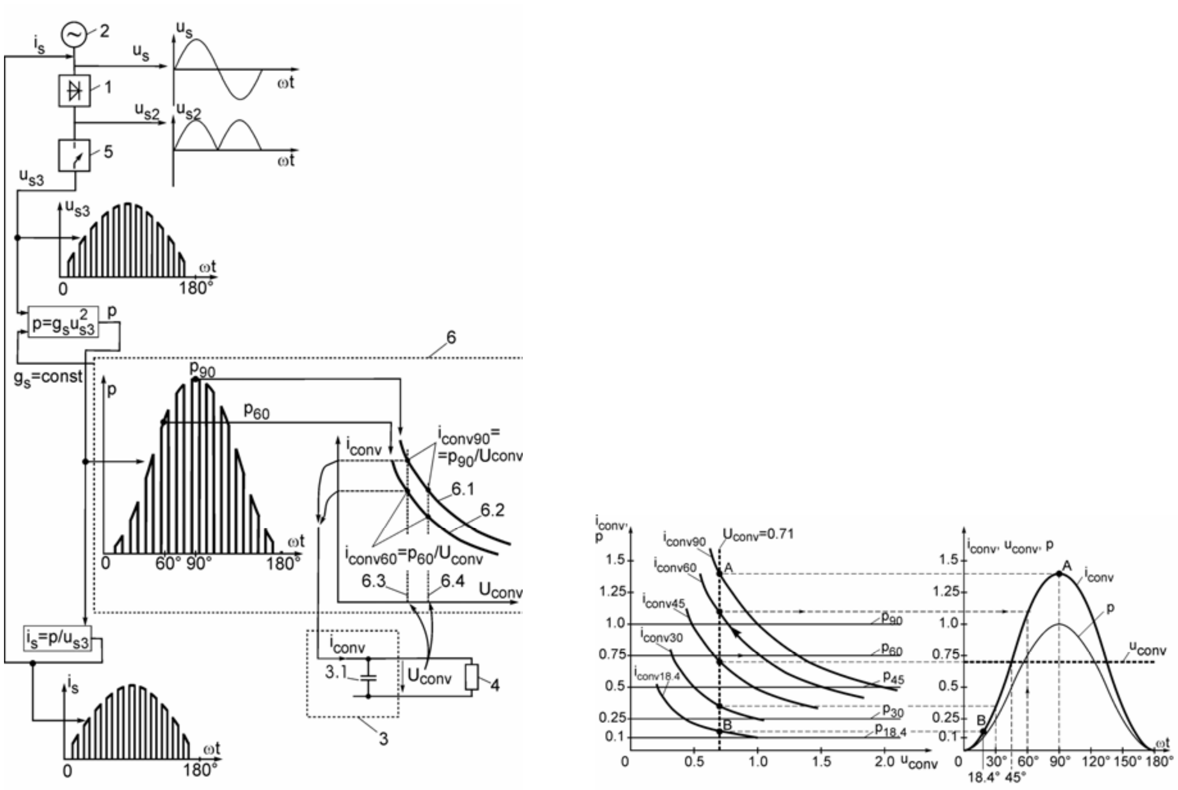
In this paper, there is presented a simple method and topology for indirect power factor correction with the help of proposed high-frequency PSA converter. In proposed topology, we combine above-mentioned advantages of PSA converter with some PFC ability.

II. DESCRIPTION OF THE METHOD AND CONVERTER

A. Principles of Operation

The method explaining diagram is presented in Fig.1.a (losses are not taken in consideration). As it is seen, the alternating mains voltage is rectified (block 1 in Fig.1.a) and then unsmoothed unidirectional mains voltage half-waves transformed into high-frequency voltage by means of switches (block 5 in Fig.1.a). This amplitude-modulated high-frequency voltage is delivered to power factor correction circuit with stabilizing input impedance (6 in Fig.1.a). This block is able to change its volt-ampere characteristic analogously to transformer. Thus, input admittance g_s of the converter circuit is constant and instantaneous value of power could be defined by multiplication of the input admittance g_s and voltage u_{s3} squared $p=g_s \cdot u_{s3}^2$. The rectified and smoothed voltage is delivered then from smoothing filter (block 3) to load (block 4). Value of output i_{conv} current is defined by dividing instantaneous mains power p by filter voltage U_{conv} ($i_{conv}= p / U_{conv}$).

The value of current delivered to the filter is forming automatically, since converter circuit is constructed so that there is an inversely proportional dependence between output voltage U_{conv} and current i_{conv}. In case when input voltage u_{s3} is not changing, converter delivers a constant power defined as $p=U_{conv} \cdot i_{conv}$=const and which is independent of the output voltage. In case of varying input voltage u_{s3}, instantaneous power p depends only on instantaneous value of input voltage u_{s3} (if losses are not taken into consideration).



a) **b)**

Fig.1. Diagram of proposed method for power factor correction in AC/DC converters (a), and graphical representation of instantaneous power supplied from mains to the smoothing filter regardless of voltage on the smoothing filter (b)

In Fig. 1.a, there are curves 6.1 and 6.2 of inversely proportional relation between voltage U_{conv} and current i_{conv} for instantaneous powers p_{60} and p_{90} (index numbers 60 and 90 are electrical degrees of mains voltage angular frequency ωt). Forming of output current is illustrated in Fig.1.a by two vertical lines 6.3 and 6.4, which are corresponding to two different voltages U_{conv} on the filter capacitor. The value of current i_{conv} delivered to the filter is defined by points of intersection of the exponential curves 6.1 and 6.2, and vertical lines 6.3 and 6.4. Provided that in every time instant instantaneous power p taken from mains is proportional to square of mains voltage u_s and delivered to the smoothing filter regardless of the smoothing filter's voltage, so the shape of mains current i_s(t) is automatically similar to shape of mains voltage. Thus shaping of current waveform in time domain could be described by mathematical relation

$$i_s(t) = p(t)/u_s(t) = g_s[u_s(t)]^2/u_s(t) = g_s u_s(t) \qquad (1)$$

where $i_s(t)$ – mains current; $p(t)$ – power; $u_s(t)$ – mains voltage; g_s – proportionality constant, which is to characterize an equivalent admittance.

The role of transformer, having fast-changing turns ratio, plays here a circuit connected between mains and smoothing filter and it has to correspond the next two requirements: the first one, input impedance of the converter circuit is constant and consequently the instantaneous power consumed from mains is directly proportional to mains voltage squared, and the second, instantaneous values of current and voltage supplied from converter circuit to the smoothing filter are inversely proportional and therefore, the instantaneous power delivered to the smoothing filter is not depending on voltage in case of filter with capacitor or on current in case of filter with choke. For instance, if voltage on the filter capacitor is 2 times lower than mains voltage then because of inverse proportion, input current of filter increases 2 times compared to mains current, and thus instantaneous power is not changing. This fact makes possible to consume power from mains proportionally to instantaneous value of mains voltage squared. It means stabilization of input impedance that was the purpose. The advantage of this method is in a fact that there is no current or voltage control needed. It is only necessary to provide the required ratio between mains voltage and instantaneous power as well as between instantaneous values of voltage and current in output filter. But implementing described power factor correction method leads to increased pulsation of load voltage (in case of resistive load) that could be a drawback of the method. Namely, constant power is delivered to load and accordingly to the proposed correction method, it is not depending on value of load resistance. If load resistance increases, the load current is decreasing, but at the same time load voltage is increasing and therefore power remains same. By output open-circuit, voltage becomes theoretically infinitely large and by short-circuit current becomes theoretically infinitely large. However in practice these extremes are limited that causes some degradation of power factor.

In Fig.1.b, there is shown in details way of supplying instantaneous power p from mains to the smoothing filter at different time instants. In the left part of Fig.1.b, there are shown curves i_{conv90} to $i_{conv18,4}$ of inversely proportional dependence between smoothing filter voltage u_{conv} and input current i_{conv} and there are also horizontal lines p_{90} to $p_{18,4}$ of instantaneous power supplied from mains. The voltage on the smoothing filter is chosen 0,71 relative units. The instantaneous values of the current delivered to smoothing filter i_{conv} are defined here by intersection points of current curves $i_{conv18,4}$ to i_{conv90} with dashed line u_{conv}=0,71. In the right part of Fig.1.b, there is shown curve of current delivered to the smoothing filter i_{conv} and there are also shown above mentioned points A and B on this curve. It is also shown voltage of the smoothing filter u_{conv} (horizontal dashed-line) and curve of the power p delivered to the smoothing filter. The power curve is defined here by multiplication of the smoothing filter voltage u_{conv} and current i_{conv} ($p=u_{conv}\cdot i_{conv}$).

B. Proposed Converter - Switch-mode PSA converter

Properties of the mains frequency PSA converter could be found in [2]. To keep above mentioned ratios with reasonable accuracy is possible by implementing a proposed high frequency PSA converter.

Along with that, increasing the supply voltage frequency in PSA converter makes the size of converter smaller. The topology of one possible embodiment for switch mode PSA converter is shown in Fig.2. The frequency-increasing unit (generalized inverter circuit) is connected here ahead of PSA converter. The frequency-increasing unit having PSA converter (7 in Fig.2.) is connected between input rectifier bridge (1 in Fig.2.) and smoothing filter (3 in Fig.2.). High frequency PSA converter is not functioning here as a higher harmonics filter as it was at mains frequency [2]. The practical effect achieved is a result of using inversely proportional dependence between output voltage and current in the converter. Supply voltage of inverter is not a constant DC voltage, as it is common in case of AC/DC converters with bulky capacitor connected after mains rectifier, but there are unsmoothed half-waves of mains voltage, which are pulsating from almost zero to mains voltage amplitude value. The frequency-increasing unit could be implemented with a single switch, as it is in Fig.2, or with bridge inverter topology. The output voltage of such inverter is a square wave with modulated amplitude.

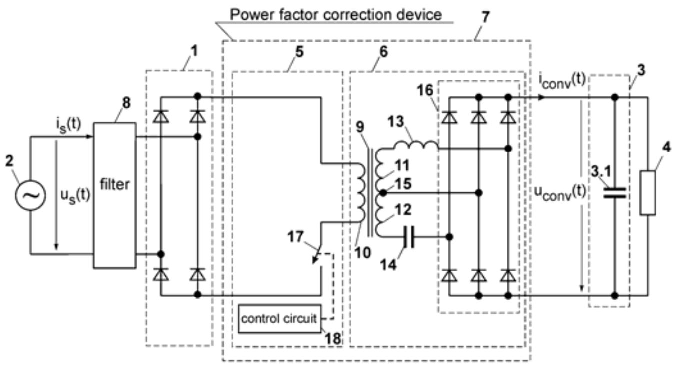


Fig.2. Switch-mode single-switch PSA converter with PFC

Due to the output characteristic of PSA converter it is possible to stabilize input impedance when instantaneous value of the voltage on both secondary windings is higher than voltage on the capacitor of output smoothing filter. Consequently, in the range of low instantaneous values of mains voltage the input impedance of converter increases and distortion appears in mains current. The range of constant output power independent of the voltage is relatively narrow for proposed uncontrolled PSA converter. Therefore, mains current distortion *THDi* in case of single-phase rectifier and described above correction is 10 – 40 %, as it is shown in Fig.3. It is also obvious that at higher values of load back-emf the mains current (curve i_s) appears only when instantaneous value of mains voltage (curve u_s) is raised enough. Mains current distortion is the smallest while operation range is close to short-circuit and increases with back-emf increasing.

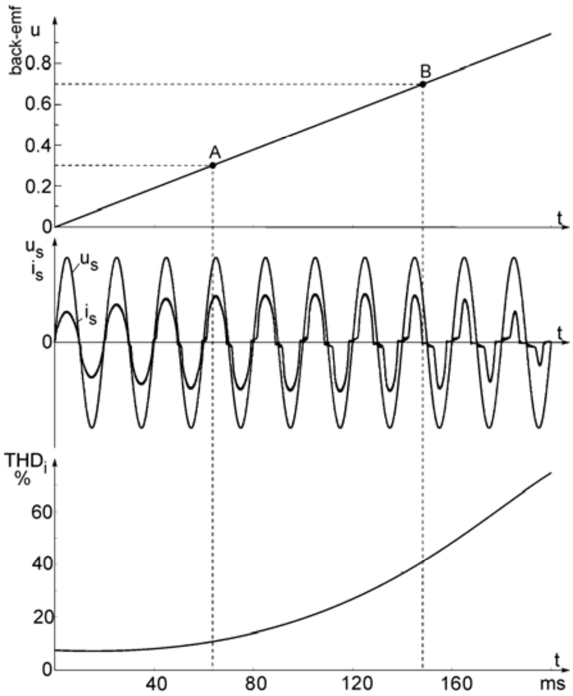


Fig. 3. Simulated waveforms of mains current is and *THDi* when back-emf of load changes from zero to no-load voltage

Thus, it is unpractical to use converter in the range close to no-load. The practical operating range is about 0.3 to 0.7 of no-load voltage as shown between points A and B in Fig.3. In the interval 0 to 0.3 of no-load voltage (range close to short-circuit) the operation is possible as it is not causing any overloads in the converter and mains current distortion remains small. But this range is unpractical for permanent operation because of lower power delivered to load and smaller efficiency of the converter. The decreasing of mains current during operation near short-circuit area is caused by converter automatically switching into the parallel resonant mode. It is possible to reduce distortion factor by adding an active correction. For this purpose capacitive branch of the PSA converter could be provided with adjustable current by-pass circuit which extends the range of constant power of the converter. But this solution remains beyond the scope of given paper.

If it is required to regulate the output power of AC/DC converter, a simple pulse width control of the inverter circuit could be applied. Under such control, shape of mains current is not changing significantly.

C. Operation in a Mains Cycle

The AC/DC converter depicted in Fig.2. is operating in the following way: voltage $u_s(t)$ is supplied to rectifier bridge (1 in Fig.2.) through the EMI/RFI filter. There are unidirectional unsmoothed half-waves of mains voltage appears on the output of rectifier bridge. The switches in frequency-increasing unit transform these half-waves into amplitude-modulated high-frequency voltage. This voltage is applied to primary winding of the transformer, which is a part of PSA converter. Because of input voltage alternation, changes also converter's

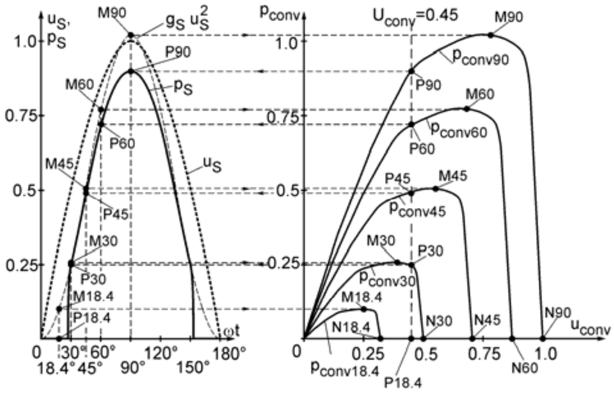
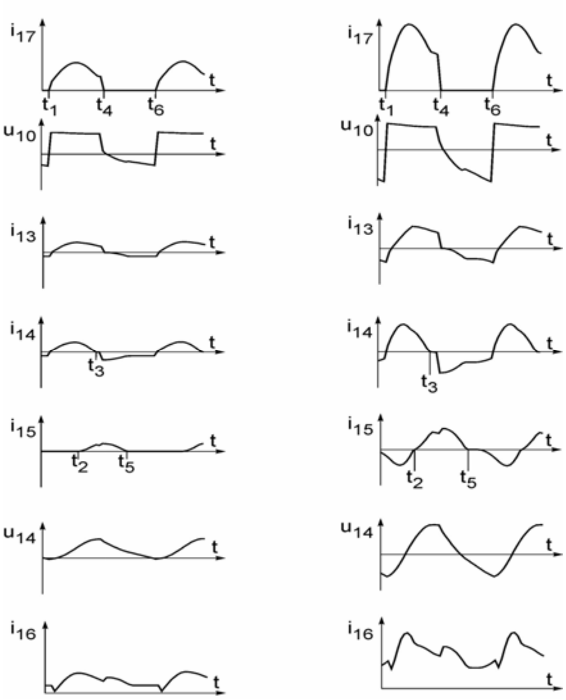


Fig.4. Graphical representation of the shaping of power waveform on AC side on the basis of interdependency between output voltage and output power of the PSA converter
(M – amplitude value, N – no load, P – instantaneous power)

output no-load voltage and maximal power, which it can give at corresponding voltage, as shown in Fig.4. In the right part, there are output power curves p_{conv} represented as a function of voltage u_{conv} on the output capacitor. For every instantaneous value of mains voltage, there is its own output power curve. There is also shown voltage on the filter capacitor as u_{conv}=0.45 relative units and represented as a vertical dashed-line. This dashed-line cuts output power curves p_{conv90} to $p_{conv18,4}$. Resulting intersection points of instantaneous powers P90 to P18.4 define as instantaneous power delivered to smoothing filter so instantaneous power supplied from the mains since losses are not taken in account. The points of the instantaneous power P90 to P18.4 found in the right part of Fig.4 are transferred to the left part where changing in time instantaneous power curve p_s is constructed. The shape of curve p_s is to some degree different from shape of the ideal power curve defined in (1). It follows that shape of mains current is also to some degree different from shape of mains voltage u_s and power factor correction is not perfect. The reason is in output power p_{conv} of PSA converter, which changes to zero at no-load and at short-circuit. Improvement of the correction is basically possible by extending the range of constant power with by-pass circuit, as it was mentioned above.

D. Operation in a Switching Cycle

The simulated oscillograms represented in Fig.5. and Fig.6. describe processes taking place in the PSA converter having a single switch topology. In the figures, there are shown current i_{17} in switch 17, current i_{10} in primary winding of the transformer, current i_{13} through coil, current i_{15} from common connection terminal (CCT) of secondary windings of transformer, capacitor current i_{14} and voltage u_{14} , and also current i_{16} supplied from the output bridge rectifier to smoothing filter. At first, we review oscillograms in Fig.5., which are corresponding to 30 electrical degrees from beginning of mains half-cycle.



Figs. 5. and 6. Oscillograms of currents and voltages in PSA converter when instantaneous value of mains voltage is half (5) and whole (6) of its amplitude value

Stage 1: $t=(t_1 \ldots t_2)$ - The control circuit turns on the switch. Current through the switch and primary winding starts increasing. The negative currents in secondary windings drop to zero and become then positive. Current in the CCT is equal to zero at this time instant. Thus, converter is in a series resonant operation mode. At the same time capacitor is charging and its voltage increasing.

Stage 2: $t=(t_2 \ldots t_3)$ - The current appears in CCT. The current i_{15} appears since the part of the current in secondary winding 11 is delivered directly to the output rectifier bridge and this part of the current is not passing through another secondary winding.

Stage 3: $t=(t_3 \ldots t_4)$ - Current through capacitor drops to zero since capacitor voltage has increased enough. After that, current from transformer is delivered to rectifier bridge only through the winding 11. Due to this transformer ratio is higher then it was during time period t_1 to t_2 when windings 11 and 12 were operating in series. Thus, transformer ratio is changing automatically under the influence of circuit voltages and currents.

Stage 4: $t=(t_4…t_5)$ - The control circuit turns off the switch. Current through capacitor appears in negative direction that starts to discharge capacitor. The primary winding's voltage changes to negative. Current in CCT starts decreasing and current i_{13} increases in negative direction.

Stage 5: $t=(t_5…t_6)$ - Current in CCT becomes zero and windings' currents become equal. Hereby, the converter is again into complete series resonant mode. At time instant t_6, control circuit turns the switch again and described above cycle is repeating.

The voltage and current oscillograms shown in Fig.6 (at mains voltage amplitude), are not too different compared to the oscillograms shown in Fig.5, except for the current that passes from CCT to bridge rectifier. In Fig.6, duration of this current in one switching period $(t_1$ *to* $t_6)$ has significantly increased. It could be explained in the following way, as CCT current appears only when voltage of the one of secondary windings together with voltage on resonant capacitor or coil exceeds voltage on capacitor of the smoothing filter, so during maximal instantaneous value of mains voltage this condition is running longer compared to previous condition when secondary windings are connected mainly in series and current through CCT is low. During time intervals when instantaneous value of mains voltage is high, current i_{15} increases significantly and in this case it means increasing of transformer turns ratio.

III. EXPERIMENTAL RESULTS

In order to verify the operation of the proposed converter, a prototype with MOSFET Full-Bridge inverter topology was built and tested firstly for low powers. The switching frequency of 40 kHz was selected. Converter includes a high frequency transformer with tapped secondary winding having 10:1:1 turns ratio. For the first time unit was tested with supply voltage 50 V RMS, 50Hz while resistive load was changing from no-load to short-circuit. The relative duration of control pulses for transistors was set at 0.4. Output characteristic for this case is presented in Fig.7. It is seen that it has a falling nature that could be advantageous for MMA arc welding. Also it is evident that short-circuit current is naturally limited. On the next Fig.8, mains current is shown as a function of load voltage. It is seen that in case of output short circuit input current becomes even less than current in nominal operation mode.

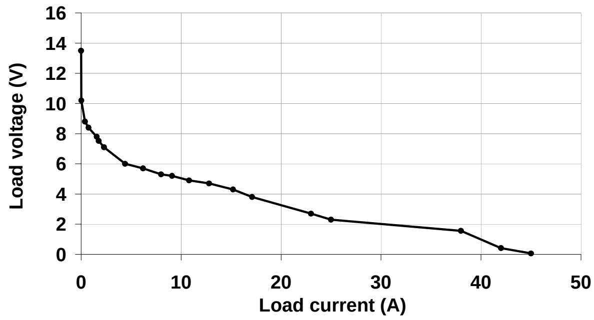


Fig.7. Output characteristic under resistive load variation

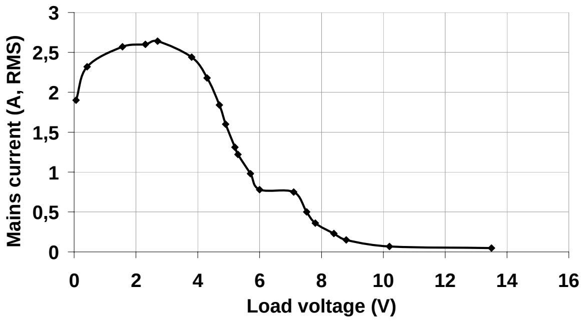


Fig.8. Mains current under resistive load voltage variation

In Fig.9, there is presented input current THD_i at different load voltages. It remains less then 10% up to load voltage 7 V. Then it increases sharply, but at the same time the value of input current decreases as it is seen in previous figure.

Fig.10 shows the oscillograms of filtered mains current and voltage at resistive load of 0.3 Ohm. It is seen, that the mains current is nearly sinusoidal and in phase with the mains voltage. The measured harmonic distortion (THD_i) of mains current is 4.5%.

Fig.11 shows the filtered mains current and voltage during charging the battery. The measured harmonic distortion (THD_i) of mains current is 25%. The current waveform and harmonic distortion are coincident well to the theory and simulation waveforms shown in Fig.3.

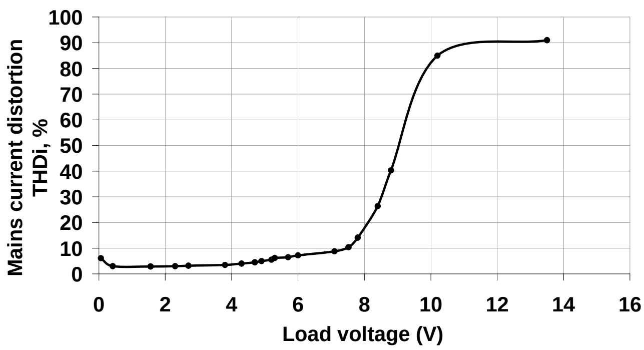


Fig.9. Mains current THD under resistive load voltage variation

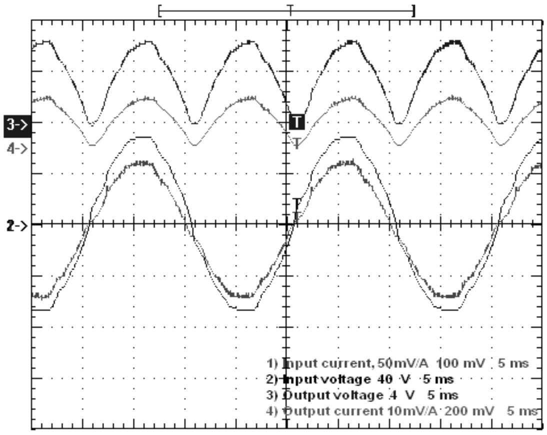


Fig.10. Mains current (1) and voltage (2) waveforms, and output voltage (3) and current (4) at a resistive load equal to 0.3 Ohm.

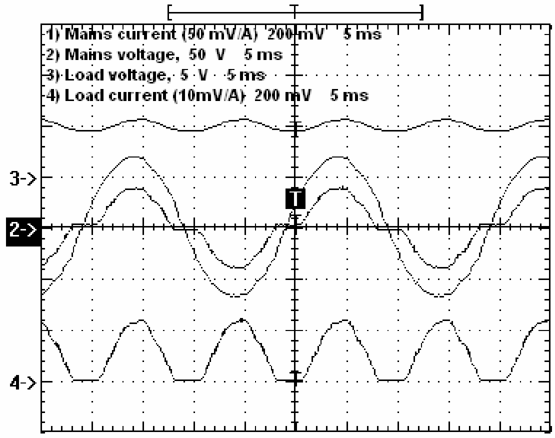


Fig.11. Mains current (1) and voltage (2) waveforms, and output voltage (3) and current (4) during battery charging.

IV. CONCLUSION

In this paper, a method for indirect power factor correction in AC/DC converter was proposed. It comprises rectifying of alternating mains voltage into unidirectional unsmoothed half-waves, transforming the unidirectional unsmoothed half-waves (by means of switches) into high frequency voltage and inputting this high frequency voltage into power factor correction circuit with stabilized input impedance. The stabilizing of input impedance is achieved by keeping an inversely proportional dependence between an instantaneous value of current supplied to input of a DC-voltage smoothing filter and instantaneous value of input voltage on the DC-voltage smoothing filter. This is realized by means of automatically (without any control) changing turns ratio in PSA converter. Nevertheless, exploiting the natural output characteristics of the PSA converter is possible to stabilize the input impedance only in time intervals when instantaneous value of voltage on both secondary windings is higher then voltage on smoothing filter capacitor. In the range of mains voltage low instantaneous values the input impedance of the converter increases and distortion in mains current appears. Thus, the acceptable level of mains current distortion is achievable when the of output voltage is in the range 0…0.7 of no-load voltage.

The nearly constant output power is obtained in such kind converter. This means if we increase load current by decreasing load resistance, the voltage is decreasing inversely proportionally to the current. It is useful in some cases, for example, supplying electric arc or charging batteries.

The output voltage of this converter can be stabilized and also controlled, if a feedback circuit used, which changes the relative duration of control pulses. The using of such feedback circuit does not change significantly the shape and distortion of mains current. Although, significant pulsation of output voltage in case of resistive load could be a drawback for some consumers, the converter based on the described method provides additional advantages.

Firstly, as the PSA converter includes transformer, so along with power factor correction, the galvanic separation from mains and required voltage level are obtained. This way, the overall simplicity of the solution is achieved.

Secondly, in case of output short-circuit the output current is not increasing more then 2 times of the rated current and currents in all circuit elements remain approximately at the level of rated current. The limitation of the output current during short-circuit originates from the PSA converter [2], which switches automatically into parallel resonant mode. It means that short-circuit protection for DC side generally is not needed.

Third advantage is a fact that instead of alternating voltage the PSA converter could be supplied with unidirectional DC voltage pulses by means of one-transistor switch (chopper). Hereby, in transformer windings appears alternating voltage because of the capacitor recharging process in LC resonant circuit of the PSA converter. This enables to reduce size of the transformer.

Fourth estimated advantage for bridge topology is in a reduced switching currents and losses in switches and diodes, due to the PSA converter operation peculiarities.

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